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Physical Model Study of Cross Vanes and Ice

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COVER: Cross-vane structure built in the flume at ERDC/CRREL

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Abstract: In recent years, channel restoration and streambank stabilization projects have been turning towards “natural” methods, such as cross vanes and rock weirs. Successful applications help control bed and bank erosion, provide flow diversity, re-connect floodplains, and improve habitat for fish and wildlife. Currently little design guidance is available for constructing these structures on ice-affected rivers.

This study used physical and numerical models to address the impact of ice runs on in-stream structures. A series of cross vane structures were tested, under conditions of an ice run, in a straight model flume with a moveable bed. Physical model results were then compared to numerical simulations using the state-of-the art DynaRICE ice-hydraulic model.

Study results support existing design guidance for grade-control structures that recommends placing them in free-flowing sections of river rather than backwater reaches, which are naturally more prone to ice jamming. The two models produced very similar results in terms of hydraulic and ice passage processes and improved our understanding of the interaction of ice hydraulics on in-stream structures. This study fell short of replicating the physical model results in the numerical model. Further experiments and simulations are proposed to better simulate ice jam conditions in the physical model.

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Contents

Figures and Tables.....	iv
Preface.....	v
Unit Conversion Factors.....	vi
1 Introduction.....	7
2 Background.....	8
3 Methods.....	9
3.1. Physical Model	9
3.1.1. Instrumentation.....	10
3.1.2. Cross-Vane Structures	12
3.1.3. Sediment Size Distribution	13
3.1.4. Sediment Scaling and Scour Processes	13
3.1.5. Ice Passage Tests.....	18
3.2. Numerical Model Simulations.....	20
4 Results.....	24
4.1. Flume Experiment Results	24
4.1.1. Ice Discharge and Wave Attenuation.....	25
4.1.2. Water Surface Profiles During Ice Passage Tests	27
4.1.3. Ice Effects on Structures.....	29
4.2. Numerical Model Results	29
5 Summary and Conclusions.....	33
6 References	36
Appendix A: Summary of Flume Tests.....	38
Report Documentation Page.....	39

Figures and Tables

Figures

Figure 1. Flume model plan view.....	12
Figure 2. Time-lapse image of cross-vane flow field	13
Figure 3. Cross-section view of cross-vane structures.....	15
Figure 4. Grain-size distribution	16
Figure 5. Vanoni critical water velocity V_{cri} vs. mean grain size compared to Froude-scaled water velocity.....	18
Figure 6. Contour map of Station 50 cross vane after scour.....	19
Figure 7. Model ice-piece size compared to other ice-piece size distributions	20
Figure 8. Ice discharge vs. time at various locations along the flume	21
Figure 9. Finite element mesh used by the DynaRICE ice-hydraulic model	22
Figure 10. Bed elevation and simulated open water velocity in the vicinity of the most downstream cross vane	23
Figure 11. Near ice stoppage at Cross Vane 2	26
Figure 12. Ice discharge vs. time at various locations along the flume (50-gpm model)	27
Figure 13. Ice discharge vs. time at various locations along the flume (25-gpm model)	27
Figure 14. Water surface profiles during 50 gpm ice passage test with structures.....	29
Figure 15. Water surface profiles during 25-gpm ice passage test with structures.....	29
Figure 16. Damage to Cross Vane 2 during ice run	30
Figure 17. Simulated water, ice, and bed profiles and average water velocity for the typical ice case.....	32
Figure 18. Simulated water, ice, and bed profiles and average water velocity for the heavy ice case.....	32
Figure 19. Ice thickness and ice velocity in the vicinity of the downstream cross vane for typical ice case under relatively steady-state conditions.....	33
Figure 20. Ice thickness and ice velocity in the vicinity of the downstream cross vane for heavy ice case just before jamming	33

Tables

Table 1. Blackfoot River and model parameters.....	11
Table 2. Important parameters used in the ice-numerical simulations.....	22
Table 3. Flume test results	25

Preface

This report was prepared by Carrie M. Vuyovich, PE, and Andrew M. Tuthill, PE, Research Hydraulic Engineers, Remote Sensing/Geographic Information Systems (RS/GIS) and Water Resources Branch, and by John J. Gagnon, Civil Engineering Technician, Engineering Resources Branch (ERB), US Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire.

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This report was prepared under the general supervision of Timothy Pangburn, PE, Chief, RS/GIS and Water Resources Branch; Dr. Justin B. Berman, Chief, Research and Engineering Division, CRREL; and Dr. Robert E. Davis, Director, CRREL.

At the time this work was performed, Colonel Richard B. Jenkins was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

Unit Conversion Factors

Multiply	By	To obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
square feet	0.09290304	square meters

1 Introduction

In recent years, channel restoration and streambank stabilization projects have been turning away from traditional methods, such as riprap and concrete, and toward more “natural” alternatives. Vanes and weirs constructed with rocks or logs to direct flow away from the banks toward the channel center are examples of such methods. These in-stream structures are often complemented by plantings to reinforce streambank soils. Successful applications help control bed and bank erosion, provide flow diversity, re-connect floodplains, and improve habitat for fish and wildlife. As interest in natural restoration methods grows, the US Army Corps of Engineers will play a larger role in their design and construction. Reliable guidance is necessary for engineers and planners to produce successful projects (Fischenich 1999).

To date, the design of rock structures has been largely empirical and little is known about their performance on rivers with ice. Zabilansky et al. (2002), in their field investigation of the Fort Peck Reach of the Missouri River, noted that further study of the river ice influences on channel and bank stabilization structures was necessary: “It is evident...that structures designed on the basis of open water conditions may produce adverse effects in conditions of ice-covered flow.” Scant design guidance currently exists for river restoration projects in cold climates.

Channel stabilization structures such as rock vanes, cross vanes, and rock weirs decrease the effective flow area. They are often constructed in populated areas to reduce the stream degradation caused by urbanization. The potential for these structures to increase the risk of ice jams is investigated in order to minimize future damages that could result. This study addresses the impact of ice in the form of breakup ice jams or major ice runs on in-stream structures, as well as how that structure might change the ice regime in the reach. Physical and numerical models are used to develop design guidance for in-stream structures and ice.

2 Background

Ice-jam-related flooding is responsible for considerable damages across the country each year (USACE 2002a). Ice jams can cause water levels to rise more rapidly and higher than during open-water events. In populated areas, major ice events can lead to serious injury or death, damages to structures such as bridges or dams, and streambank and bed erosion. Any channel modification projects in ice-prone rivers should examine the potential risk for ice jams in the design phase.

Breakup ice jams tend to occur in the spring as temperatures and water levels rise, weakening and eventually fracturing the ice cover and transporting it downstream. Ice jams form where the ice conveyance capacity of the river is reduced or where there is an obstruction in the stream. Common locations of ice jams include sharp river bends, decreases in channel slope, in-stream structures, and river confluences. The CRREL Ice Jam Database, which holds more than 14,000 records of ice events in the United States, is a good source for identifying common ice jam locations (IJDB 2005, White 1996).

Several river restoration structures are proposed on rivers with a known history of ice jams—for example, the Winooski River in Montpelier, Vermont, and the Blackfoot River in Montana. How these structures will perform under ice conditions is unknown. At least one instance of an in-stream structure exacerbating the problem is known: along the White River in Colorado, a freeze-up jam formed at a rock-weir diversion structure, flooding upstream ranchland. Potential problems include ice jam flooding at the structure, damage to the structure as ice passes over, or damage to the structure during the freeze-up or breakup of a solid ice cover.

3 Methods

Our approach was to test a common in-stream structure, the cross vane, in a straight model flume with a moveable bed. Cross vanes are being proposed on the ice-jam-prone lower Blackfoot River upstream of its confluence with the Clark Fork in Montana. This is the site of a restoration effort following the planned removal of the 100-year-old Milltown Dam, which is part of the Clark Fork Superfund Project (WestWater Consultants et al. 2005). Tuthill et al. (2005) evaluated the ice impacts of the proposed project in a study supported by Seattle District of the US Army Corps of Engineers and the US Environmental Protection Agency. The current study is modeled after characteristics of the Blackfoot River and complements research carried out in the previous one.

Cross-vane structures span the entire width of a stream and are designed to protect the banks and offer grade control by deflecting the flow toward the center of the stream over a fixed elevation of footer rocks. By design, the weirs resist flow, and planners are cautioned against building them on reaches with a high debris load because of the increased risk of flood (Washington 2004). Cross vanes were chosen for this study because they combine aspects of rock vanes and rock weirs and seem to pose the greatest threat of forming an ice jam.

For this study, the cross-vane structure was tested under conditions of an ice run. Once open-water baseline conditions were documented, three model cross vanes were built and discharge was increased to promote scour and deposition in the vicinity of the structures. A series of ice conveyance tests was carried out for both baseline and with-structure conditions. Physical model results were then compared to numerical simulations using the state-of-the art DynaRICE ice-hydraulic model (Shen et al. 2000).

3.1. Physical Model

This experiment was performed at the Engineer Research and Development Center's (ERDC) Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, New Hampshire. The physical model portion of the study investigated the performance of a series of three cross vanes in a

4-ft-wide by 120-ft-long tiltable flume, under both open water and ice conditions. Three cross-vane structures were modeled in a straight stretch of river at a 0.0024 slope. A ¼-inch mesh wire lined the walls of the flume to increase the roughness of the sides. Plastic “ice” with a realistic piece-size distribution was used to model a breakup run.

The study used an undistorted scale of 1:50 in the model design. The model tests are similar to a 200-ft-wide river of rectangular cross section with a bankfull depth of 8 ft and a bankfull discharge of about 6200 cfs. Similar full-scale characteristics can be found on the Blackfoot River in Montana. The Blackfoot River is approximately 200 ft wide with an approximately trapezoidal cross section and a bankfull depth of 7.8 ft. in the riffle sections (WestWater Consultants et al. 2005). The average January discharge is 700 cfs and, for a significant ice event to occur, Tuthill et al. (2005) estimated that the ice must be at least 10 inches thick, and the discharge must increase at least 1400 cfs above the base-flow level. The bed sediment is characterized by gravel and small boulders with a median sediment size, D_{50} , of 63 mm. Table 1 gives the model and prototype dimensions.

Table 1. Blackfoot River and model parameters.

Parameter	Blackfoot River	Model (Prototype)
Bankfull discharge	6200 cfs	157 gpm (6184 cfs)
Lower threshold breakup discharge	~1970 cfs	50 gpm (1969 cfs)
Average January discharge	700 cfs	25 gpm (985 cfs)
Width	200 ft	4.0 ft (200 ft)
Bankfull depth	6.2–7.5 ft	0.2 ft (8 ft)
Slope	0.0024	0.0024
Sediment D_{50}	63 mm	1.1 mm (50 mm)

3.1.1. Instrumentation

The discharge was measured by an in-line electromagnetic flow meter accurate to ± 2 percent. A point gage was used to measure depths in the flume. An acoustic Doppler velocity meter attached to an overhead carriage measured flow velocity. Ten pressure transducers were placed along the flume to record the water depth at one-second intervals during the tests. Figure 1 shows locations. Cameras were used extensively to

document the experiment as well as to view the flow fields using time-lapse techniques (Fig. 2).

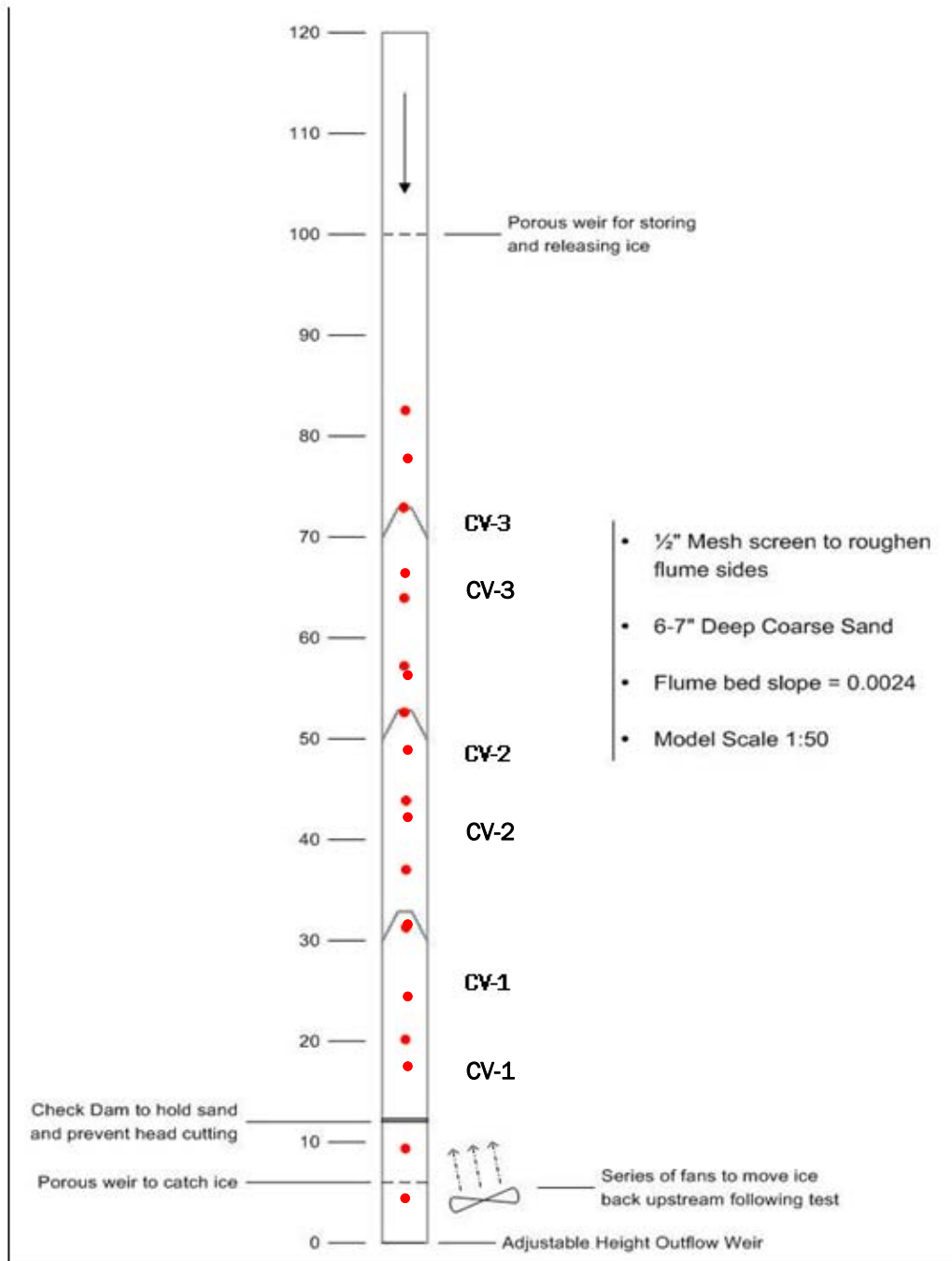


Figure 1. Flume model plan view. Red dots indicate locations of pressure transducers. "CV" denotes cross vanes.



Figure 2. Time-lapse image of cross-vane flow field.

3.1.2. Cross-Vane Structures

Cross vane design was based on existing guidance, such as Rosgen (2001), Johnson et al. (2002), and the Natural Resources Conservation Service (2001), as well as guidance provided by state agencies (Washington [2004] and Maryland [2000]). Three cross vanes were constructed in the flume at Stations 30, 50, and 70 (Fig. 1). The structures were placed five channel widths or 20-ft model apart. In terms of grade control, this was deemed a reasonable spacing since, in the pre-scour state, experiments and the HEC-RAS hydraulic model (USACE 2002b) found that water surface elevation merged with the normal depth about five channel widths upstream of the cross vanes.

The time-lapse image in Figure 2 demonstrates how the cross-vane structure re-directs flow from the channel sides toward the middle and

increases the velocity through the center. The fast-moving water in the center of the channel scours out a deeper channel, while the slow-moving water on the sides protects the banks from erosion.

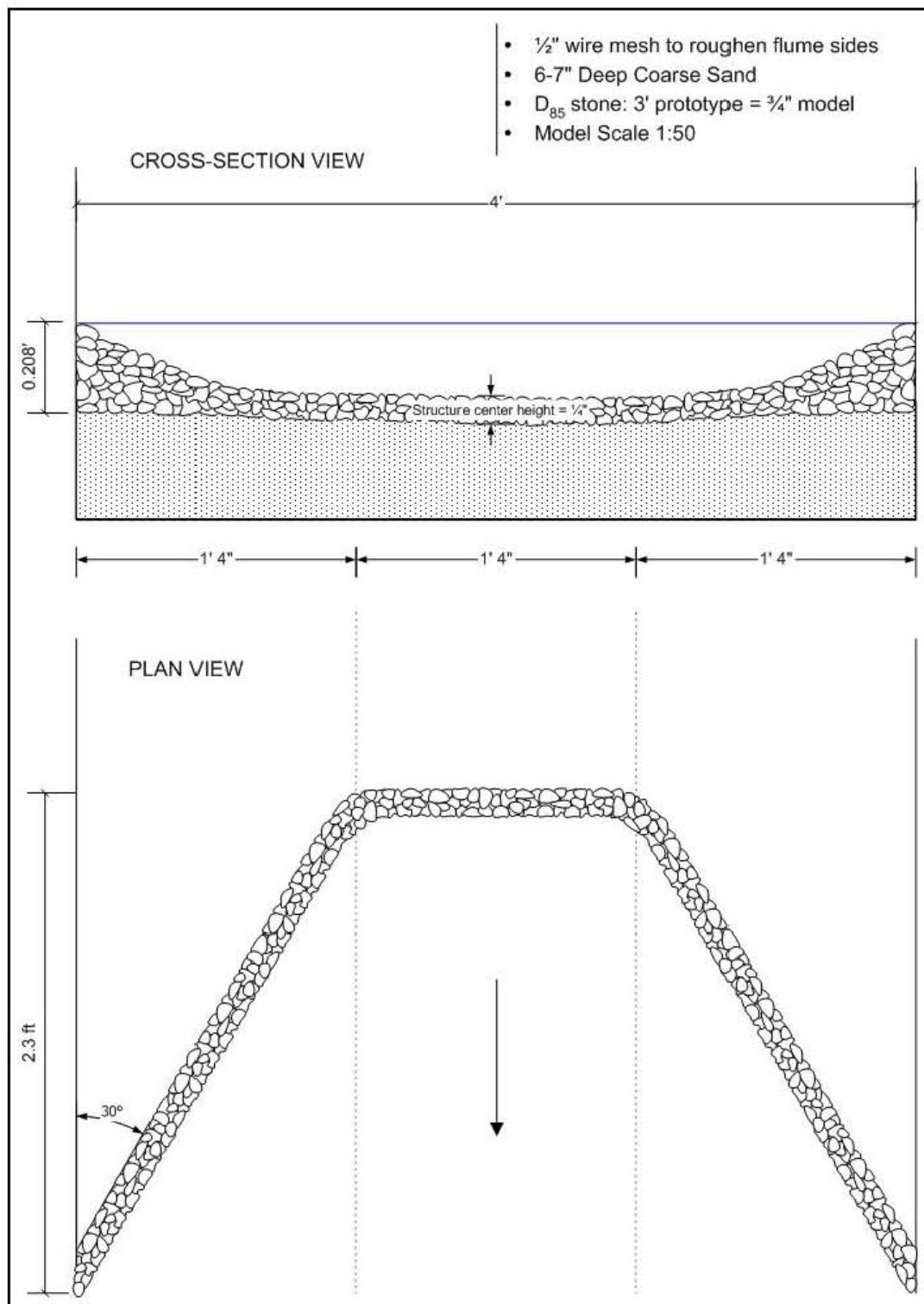
Each cross vane consisted of paired rock vanes, angled 30° upstream from the banks, and extending out one-third of the channel width. The models were constructed of 3/4-inch crushed stone, which corresponds to a full-scale rock diameter of about 3 ft. Larger footer rocks were placed within the stream bed beneath the cross vanes to prevent undermining. A central weir section connected the vane tips to complete the cross vane. The vanes tie into the bank at the bankfull depth elevation and slope downward to a minimum height about 1-ft prototype above the bed, where they join the central section. This differs from the Rosgen (2001) cross vanes, which are typically level with the existing river bed in their central section. Our cross vanes differed also in that transition from the vane to the central weir was curved, rather than angular, in plan view. Figure 3 shows a cross section and plan view of a cross vane.

3.1.3. Sediment Size Distribution

Bed sediment was well-graded concrete sand with an average grain size of about 1 mm, which scales to a prototype D_{50} of 50 mm, representing the gravel-to-cobble size range. Figure 4 shows the grain-size distribution of the sediment.

3.1.4. Sediment Scaling and Scour Processes

The purpose of the cross vane is to control grade and direct flow toward the channel center. In successful field applications, a scour hole typically forms downstream of the structure while sediment usually deposits upstream and downstream of the points where the vanes tie into the banks. It is thought that most of this scour and deposition takes place at channel-forming discharges at the bankfull level or above (Copeland et al. 2000). To form the scour holes downstream of the cross vane structures, the flume slope was increased while maintaining a constant water depth. This strategy for forming scour and deposition features was based on review of existing critical shear data and theory and experimentation.



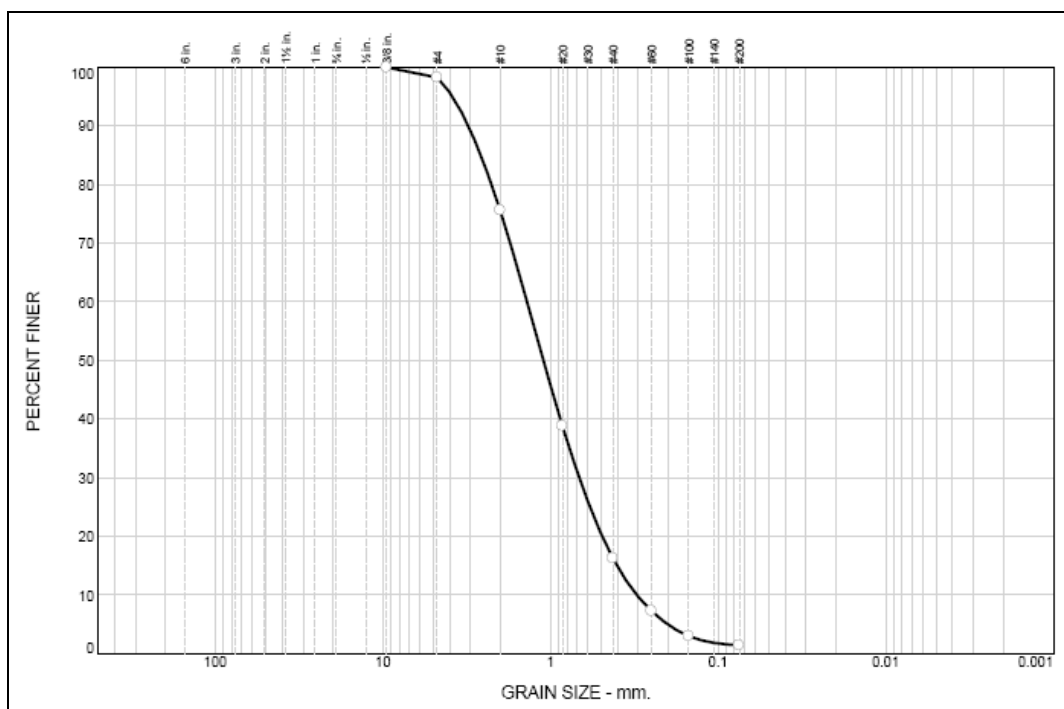


Figure 4. Grain-size distribution.

According to accepted theory (Henderson 1966), it is difficult to accurately simulate sediment transport processes in an undistorted physical model using model and prototype bed materials of the same specific gravity. Typically a material such as coal dust is used in the model with a density about half that of a natural bed material such as sand or rock. With knowledge of the critical velocity¹ of the model bed material and the bed roughness, the modeler can adjust hydraulic parameters of slope and depth to achieve water velocities needed for sediment transport. A model distortion (depth ratio/width ratio) can then be calculated to relate channel width to the desired depth.

In the present study we found that it is possible to create reasonable patterns of scour and deposition in a 1:50-scale undistorted physical model using natural sand bed material of comparable density to the full-scale bed material. For open channel flow, Froude Number similitude equates the prototype-to-model water velocity ratio V_r to prototype-to-model length ratio L_r raised to the 1/2 power.

¹ The average water velocity at which the bed material will start to move.

$$V_r = L_r^{1/2}. \quad (1)$$

The prototype-to-model ratio of bed material grain size distributions is assumed to be equivalent to the length scale.

$$D_r = L_r, \quad (2)$$

i.e., a model D_{50} of 1 mm corresponds to a prototype D_{50} of 50 mm.

Considerable research has addressed the issue of critical velocity for movement as a function of bed material size. Vanoni (1977) plots critical water velocity V_{crit} data for quartz sediment as a function of mean grain size. The following relationship can be fit to the Vanoni data:

$$V_{crit} = 1.28D_{50}^{0.46} \quad (3)$$

or, stated in terms of scaling ratios,

$$V_{crit_r} = 1.28D_{50_r}^{0.46}. \quad (4)$$

Figure 5 shows that two curves for velocity ratio vs. length ratio and critical velocity vs. mean grain size to be fairly similar within the 1-to-50 range (for the grain size case, units are mm). For example, for an average grain size of 1 mm, sediment motion should initiate at an average water velocity of about 1.0 ft/s. Assuming a model-to-prototype scale of 1:50 using Equation 1, this corresponds to a full-scale water velocity of 7.1 ft/s, quite close to the critical velocity of 7.7 ft/s predicted from the curve fit to the Vanoni (1977) data.

With the model cross-vane structures in place, discharge and average flow velocity were progressively increased to the point where significant bed movement occurred at a model discharge of 360 gpm and an average model water velocity of about 40 cm/s. For this channel-forming condition, a model with a constant normal depth of 0.20 ft was maintained by increasing the slope of the flume bed from the 0.0024 baseline condition to 0.00966. Tilting the model was necessary to increase water velocity sufficiently to scour the bed while maintaining pre-determined bankfull depth of 0.20 ft model (8 ft prot). As the bed material size distribution was

non-uniform, finer size fractions eroded first, coarsening and armoring the bed until an equilibrium condition was reached. As a result of this armoring process, average grain of the post-scour surface bed material increased about 3 mm from the pre-scour D_{50} of 1.1 mm.

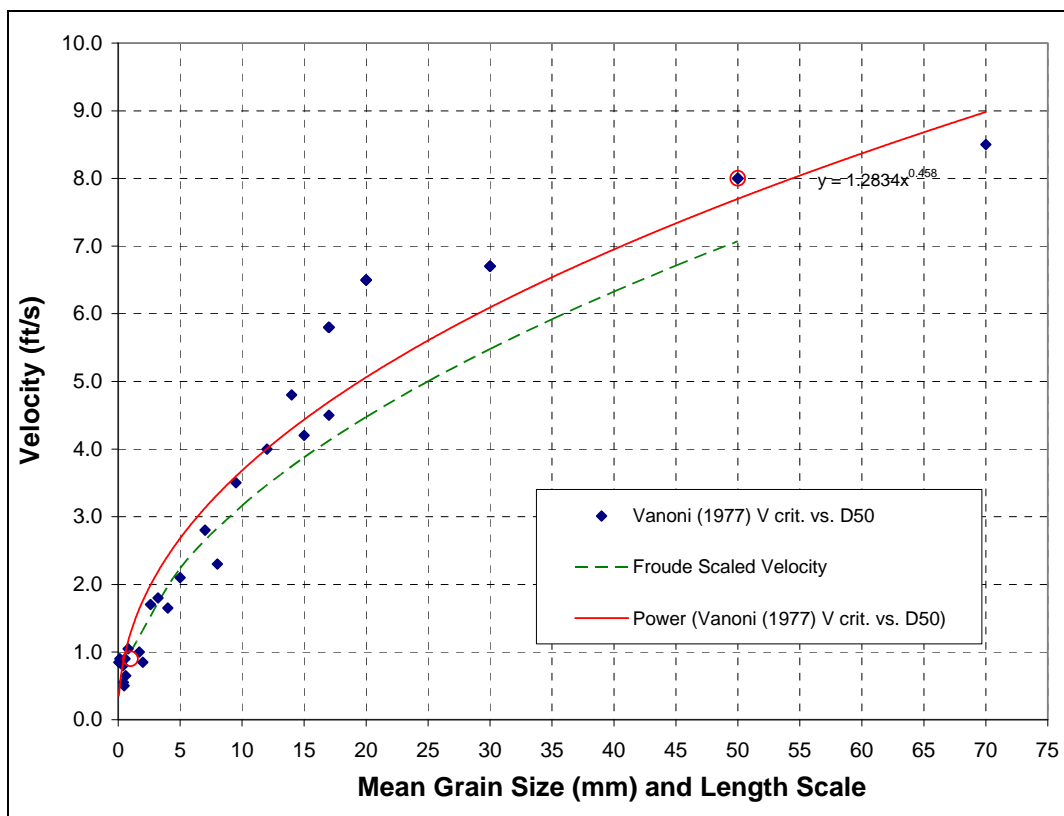


Figure 5. Vanoni critical water velocity V_{crit} vs. mean grain size compared to Froude-scaled water velocity.

Channel forming discharge, depth, and slope (360 gpm, 0.20 ft, and 0.00966) were maintained for 18 model hours to achieve reasonable scour holes downstream of the cross vanes, with some deposition of finer material along the channel sides in the vicinity of the structures. Scour hole depth averaged 0.04 ft model (2 ft prototype). Figure 6 shows the observed bed topography and average water velocity at the middle cross vane, which compares qualitatively to measured field data from the San Juan River in Colorado presented by Rosgen (2001). The slope was returned to 0.0024 for the experiments.

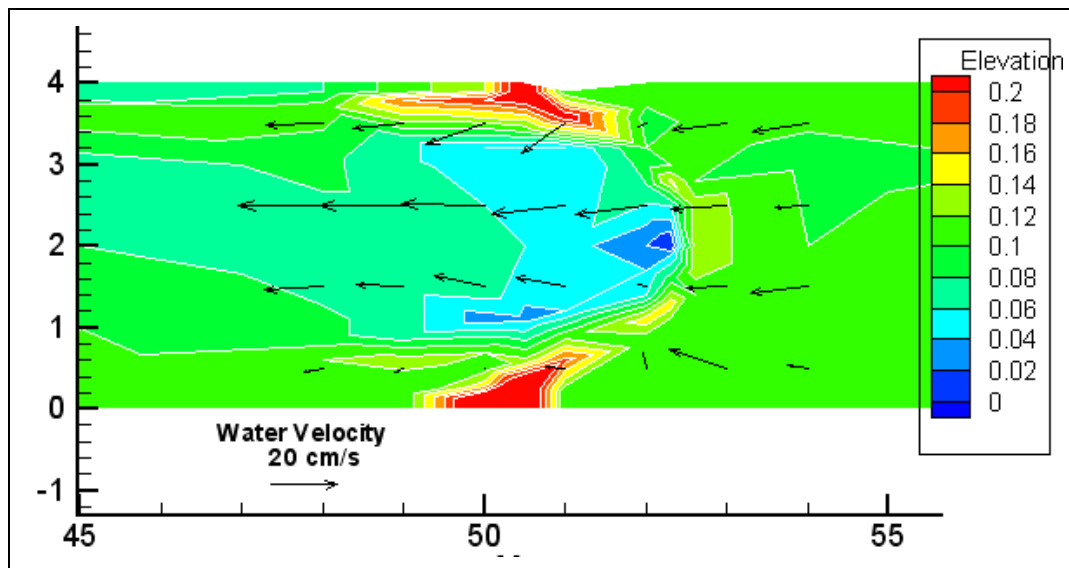


Figure 6. Contour map of Station 50 cross vane (CV-2) after scour.

3.1.5. Ice Passage Tests

A well-graded mixture of crushed and sawn polyethylene pieces was used as a model ice material to test ice passage with cross vanes. The model ice had a specific gravity of 0.92, similar to freshwater ice, and a mean diameter of 7 mm, corresponding to an average prototype ice piece size of 14 inches. The volume of broken ice pieces was assumed to derive from a prototype mile-long by 200-ft-wide by 1-ft-thick pre-breakup ice cover. The piece size distribution was based on field observations, other model studies, and measured data from the St. Claire River (Daly and Arcone 1989). For the smaller size fractions, crushed polyethylene, with a known piece-size distribution, was used. Additional ice pieces cut from $\frac{1}{4}$ -inch-thick polyethylene sheets provided the larger size fractions, creating the piece size distribution shown in Figure 7.

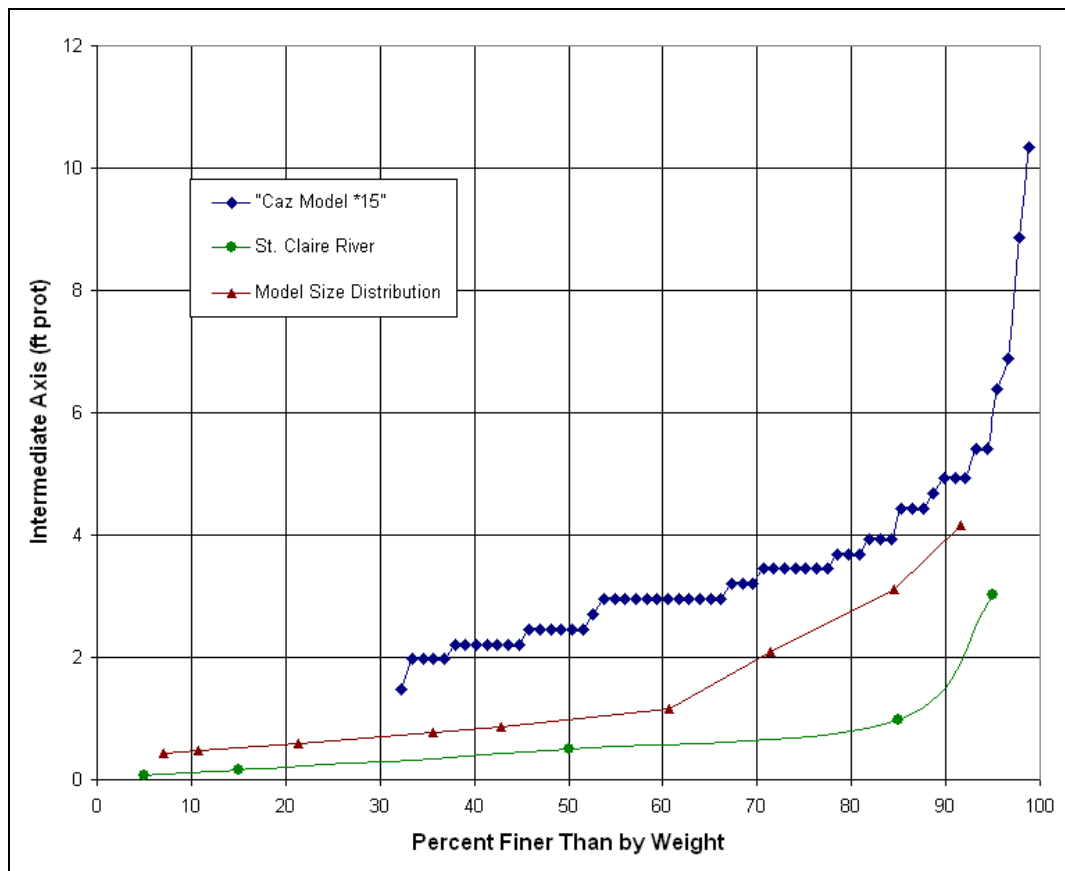


Figure 7. Model ice-piece size compared to other ice-piece size distributions.

Conditions of steady uniform flow, shown in Table 1, were established by adjusting model water inflow and the height of a downstream weir. A wire mesh retained the model ice near the upstream end of the flume. Marker pieces were placed at even intervals along the surface of the initial ice accumulation and the ice volume between the marker pieces was calculated. The ice was released, and the arrival times of the marker pieces were recorded at selected downstream locations. Assuming the ice volumes between the passing markers are equivalent to pre-release ice volumes between markers, ice discharge could then be calculated. Figure 8 illustrates ice discharge at three flume locations and the attenuation of the ice discharge wave as it travels down the flume and past the cross vanes.

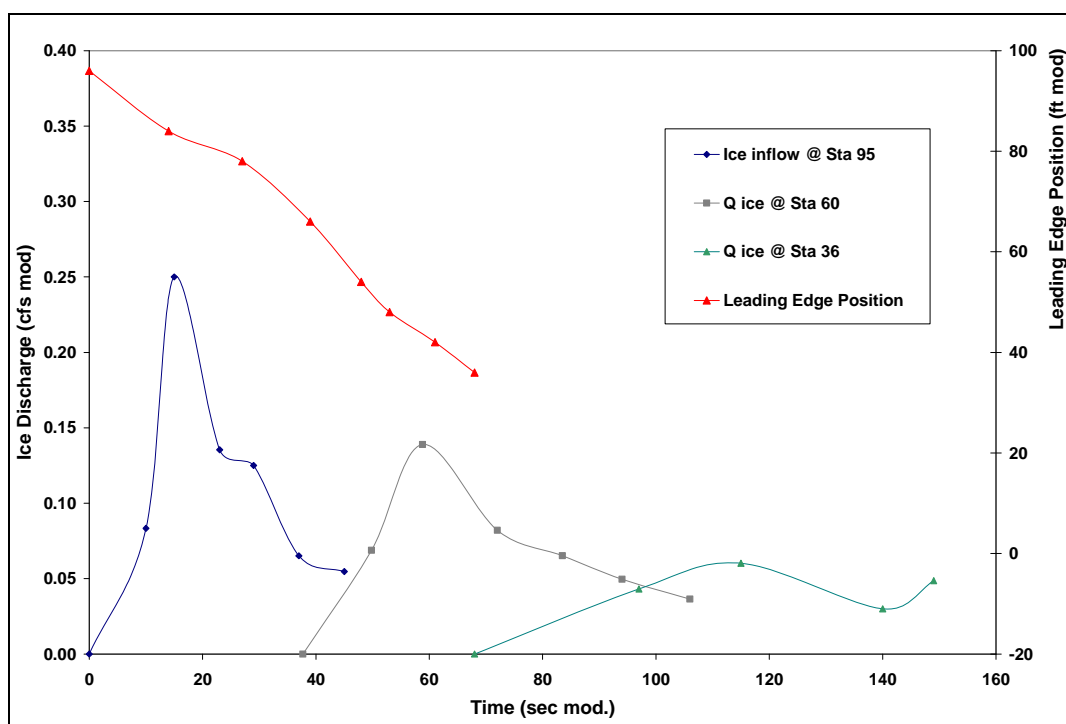


Figure 8. Ice discharge vs. time at various locations along the flume. Water discharge is 50 gpm.

3.2. Numerical Model Simulations

Parallel ice passage simulations were carried out using the DynaRICE model for river ice transport and jam evolution. (Shen et al. 2000). DynaRICE is currently the only two-dimensional model available that couples the dynamics of surface ice transport with the hydrodynamics of the flow. In the model, ice dynamics are simulated using a Lagrangian discrete parcel method (DPM) with smoothed particle hydrodynamics. This method considers the ice as a continuum, represented by a sufficiently large number of individual parcels. Each parcel has well-defined properties such as mass, concentration thickness, and velocity, and is deformable in shape. For this study, internal ice resistance and boundary frictional forces were calculated based on Mohr-Coulomb yield criteria. Simulated ice jams result from ice flow convergence, which increases ice concentration or ice thickness, internal ice resistance, and boundary friction. This reduces ice velocity, leading to further convergence, and may ultimately slow the ice to a stop. The water flow is simulated with a finite element method using the lumping technique and leapfrog time integration. The effects of seepage through the ice jam, as well as those due to ice booms, and other hydraulic structures are considered.

Important parameters used in the simulations are listed in Table 2. Because DynaRICE is unsuitable for simulating depths, velocities, and ice thicknesses as small as those used in the flume experiments, full-scale units were used in the simulations. Also, DynaRICE uses metric units.

Table 2. Important parameters used in the ice-numerical simulations.

Parameter	Description	Value
Q _w	Water discharge	55.6 m ³ /s prototype (50-gpm model)
y	Downstream open water normal depth	5.5 ft (0.11-ft model)
V _{avg}	Average open water velocity	0.54 m/s
C _{max}	Maximum ice concentration	0.7
T ₀	Initial ice parcel thickness	0.3–0.6 m
ϕ	Internal friction angle of ice rubble	46°
$\tan \phi$	Boundary friction coefficient	1.04
n _i	Manning's n for ice underside	0.02–0.06
n _b	Calculated Manning's n for channel bed	0.13
Q _i	Ice discharge	6.9 and 13.7 m ³ /s prototype (0.014 and 0.028 ft ³ /s model)

The domain of the DynaRICE model was based on the surveyed post-scour bathymetry of the flume model with the cross vanes in place. Figure 9 shows the finite element mesh and Figure 10 shows bed elevation and the open water velocity distribution in the vicinity of the lowest cross vane.



Figure 9. Finite element mesh used by the DynaRICE ice-hydraulic model.

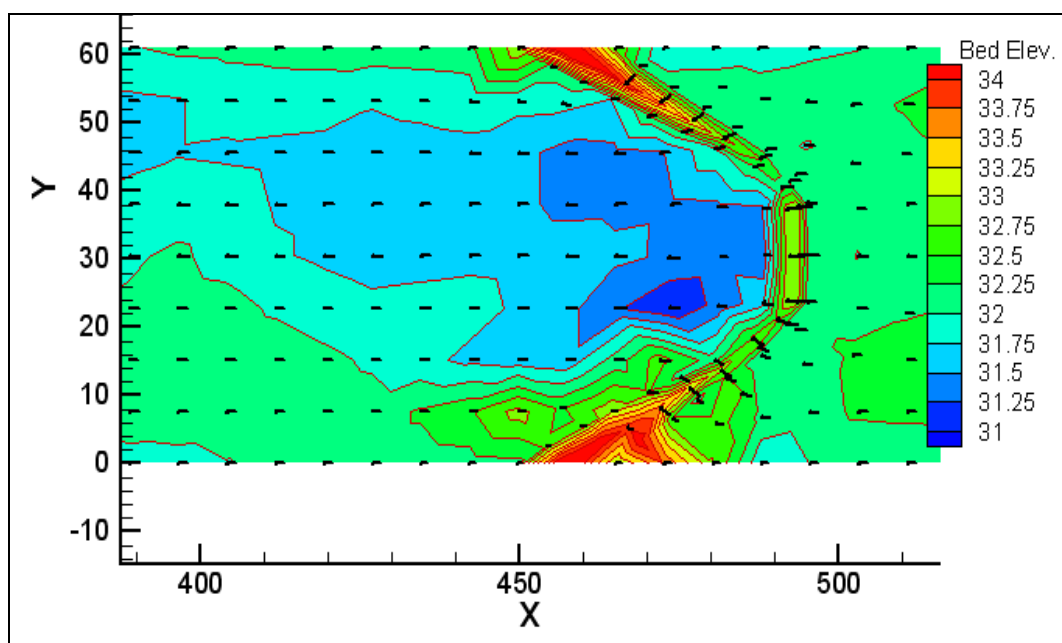


Figure 10. Bed elevation (m) and simulated open water velocity (m/s) in the vicinity of the most downstream cross vane. Constant flow of 55.6 m³/s (50 gpm model).

Simulations were done at a steady model discharge of 50 gpm corresponding to a full-scale discharge of 55.6 m³/s. This is slightly higher than the estimated lower threshold for ice breakup on the lower Blackfoot River of 1900 cfs or 54 m³/s. Under no-ice conditions, the observed downstream normal depth in the flume was 0.11 ft model or 1.67 m full scale. From one-dimensional continuity, the calculated average water velocity is then 0.25 ft/s model or 0.54 m/s prototype². Assuming this depth and velocity, with a bed slope of 0.0024, a channel bed Manning's n of 0.13 was calculated for use in the DynaRICE simulations using the Manning's equation. This relatively high n value was needed to achieve the full-scale normal depth of 1.67 m.³

Two types of simulations were done; the first at a "typical" ice discharge of 6.9 m³/s, and a second at a "high" ice discharge of 13.7 m³/s. These values correspond to model ice discharges of 0.014 and 0.028 cfs, respectively, which are somewhat lower than the measured ice discharges in the 50-gpm flume tests of ice passage over the cross vanes (see next section).

² Average velocity = discharge / cross sectional flow area

³ Since Manning's n does not scale with depth, n must be increased as depth increases to achieve correct scaling from model to prototype.

For both cases, water discharge was steady at $55.6 \text{ m}^3/\text{s}$, which is equivalent to the 50-gpm flow used in the flume experiments.

Ice discharge into the model domain Q_i was calculated as the product of maximum ice concentration C_{max} (0.7 in both cases), ice parcel thicknesses T_o (0.3 m for the typical ice case and 0.6 m for the heavy ice case), an average water velocity V_{avg} of 0.54 m/s, and a channel width of 61 m.

After an initial ramp-up period, the ice discharge at the upstream end of the model remained constant for the five-hour duration of the simulation. The model output hourly ice and water surface profiles, as well as horizontal water velocity, water depth, ice thickness, and ice velocity distributions, are shown in the results section.

4 Results

4.1. Flume Experiment Results

The following discussion focuses on the results of seven of the total 14 tests conducted. A complete listing of tests is included in Appendix A. Although the cross vanes resisted ice passage, no complete ice stoppages occurred during any of the tests (Table 3). The ice run was slowed by the structures, but the increased water velocity at the channel center kept the ice moving through. Figure 11 shows a near ice stoppage that occurred during Test 14 at the downstream cross vane at a 25 gpm-flow model.

Table 3. Flume test results.

Test number and conditions	Discharge (gpm)	Normal depth (ft)	Average velocity (cm/s)	Result
5. Open Water, no structures	25	0.07	12.5	No sediment movement
6. Open water, no structures	50	0.11	11.7	No sediment movement
7. Ice, no structures	25	0.07	12.5	No jam
8. Ice, no structures	50	0.11	11.7	No jam
12. Open water, structures	157	0.176	18.2	Document bed geometry, depths, and velocities
13. Ice, structures	50	0.11	12.5	Structures slow ice, but all ice passes
14. Ice, structures	25	0.07	11.7	Ice nearly jams at structures, but eventually passes



Figure 11. Near ice stoppage at Cross Vane 2. Water discharge is 25 gpm.

4.1.1. Ice Discharge and Wave Attenuation

In an effort to create ice jamming conditions, a high ice inflow was used. To achieve this, a thick ice accumulation of plastic ice, containing numbered marker pieces spaced at intervals, was retained at the upstream end of the flume and then released, as described in Section 3.1.5. Because the flow resistance of the retained ice caused water to pool at the upstream end of the flume, the ice release was accompanied by a surge of water. For this reason, water discharge was unsteady in the beginning of the ice tests.

The ice discharge wave attenuated as it traveled down the flume, as shown in Figure 8 (Section 3.1.5). Figure 12 compares ice passage in the 50-gpm with-structures case to the 50-gpm baseline case (Tests 8 and 13). Figure 13 makes the same comparison for the 25-gpm case (Tests 7 and 14). For both water discharges, the structures have a major effect in terms of attenuating the ice discharge by the time the wave peak reaches the lowest cross vane. In the 25-gpm with-structures case, the ice discharge has more or less leveled off to about 0.02 cfs after about 150 seconds. In the 50-gpm with-structures case the quasi-steady-state ice discharge at the lowest structure is on the order of 0.04-cfs model. These measured ice discharges guided selection of ice discharges used in the numerical model simulations, the results of which are presented in Section 4.2.

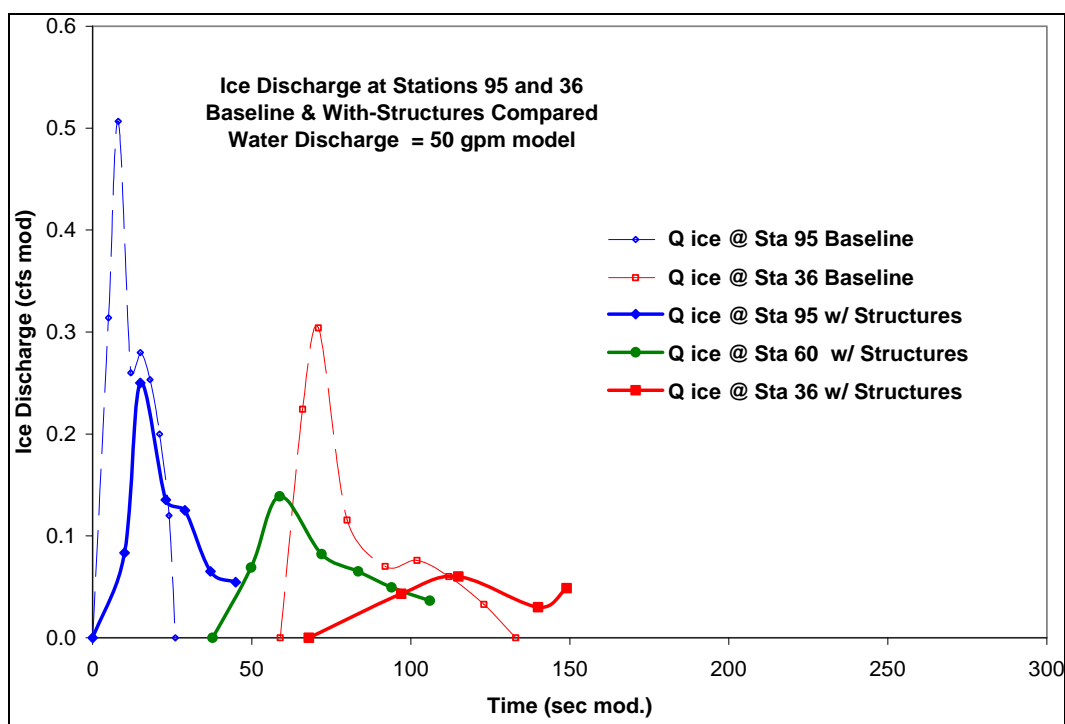


Figure 12. Ice discharge vs. time at various locations along the flume. Baseline and with-structures conditions are compared. Water discharge is 50-gpm model.

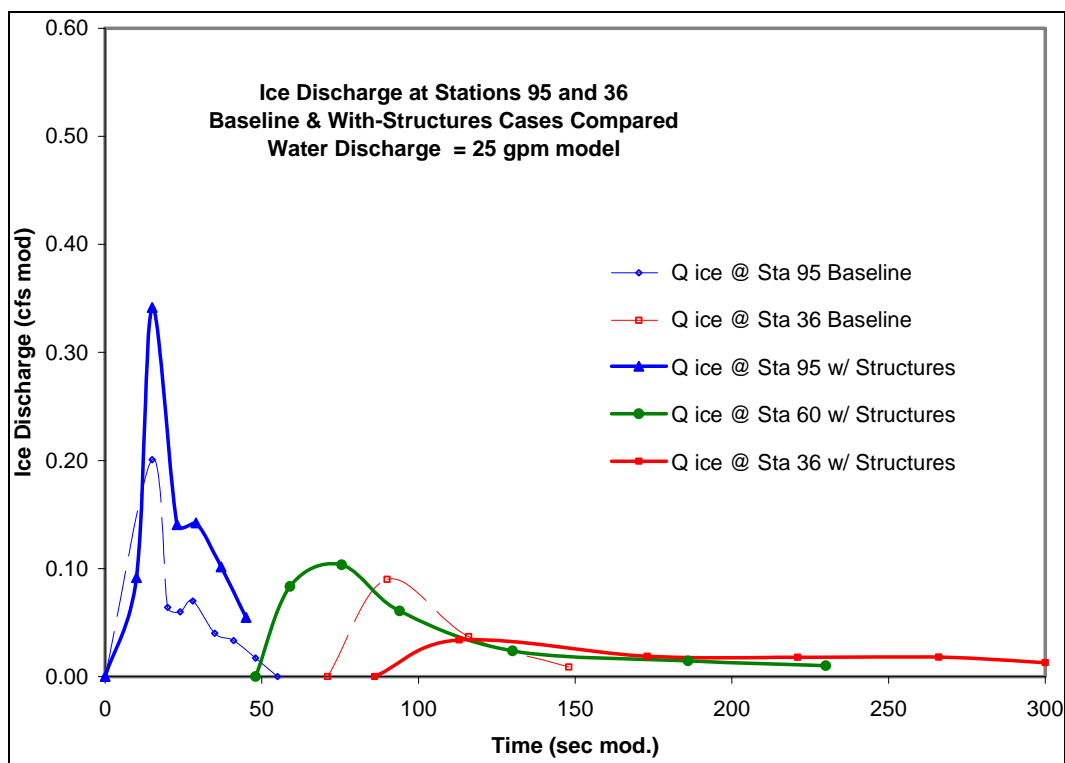


Figure 13. Ice discharge vs. time at various locations along the flume. Baseline and with-structures conditions are compared. Water discharge is 25-gpm model.

4.1.2. Water Surface Profiles During Ice Passage Tests

An array of 10 pressure transducers at the locations shown in Figure 1 recorded time-series water-level data for the with-structures ice passage Tests 13 and 14. These water level data illustrate the progress of the water and ice discharge waves as they traveled down the flume and past the structures. Figure 14 shows water surface profiles for the 50-gpm Test 13 at 15, 58, and 112 seconds⁴, corresponding to the times the ice wave peak passes stations 90, 60, and 30, as shown in Figure 12. At 15 seconds, when the ice discharge peak is at Station 90, the water wave is midway down the flume at about CV-2. Downstream of CV-2, the water surface remains at the pre-release open-water normal depth. At 58 seconds, when the ice discharge peak is just upstream of CV-2, the water wave has passed the entire flume length and flow has steadied. From 112 to 200 sec, the remaining ice passes through the flume with a water surface profile more or less parallel to the pre-ice open-water normal-depth water-surface profile, except for some staging upstream of CV-2.

Figure 15 shows water surface profiles for the 25-gpm test 13 at 16, 62, and 113 seconds, corresponding to the times the ice wave peak passes Stations 90, 60, and 30, as shown in Figure 13. Similar to the 50-gpm case, the water wave precedes the ice discharge peak at times 16 and 62 seconds. The 113-second water surface profile shows a near ice stoppage at CV-2 that lasts through time 250 seconds. By time 350 seconds, the ice has cleared the flume and the water-surface elevation has returned to the open-water normal depth.

⁴ Time zero corresponds to the release of the ice from the upstream end of the flume.

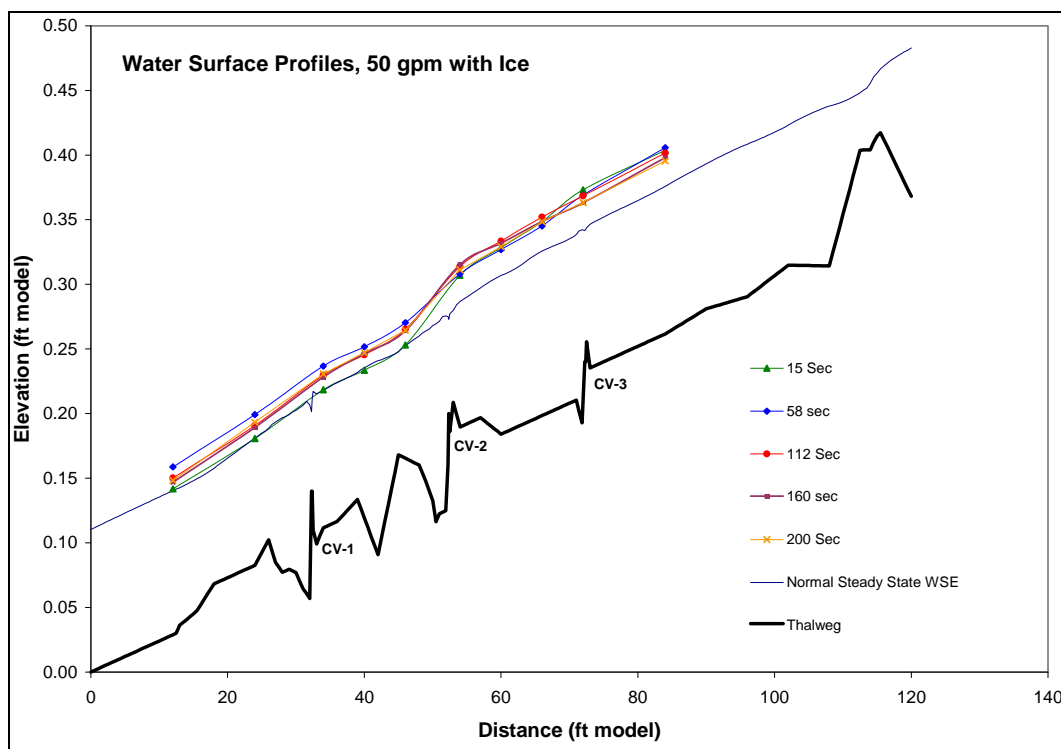


Figure 14. Water surface profiles during 50-gpm ice passage test with structures.

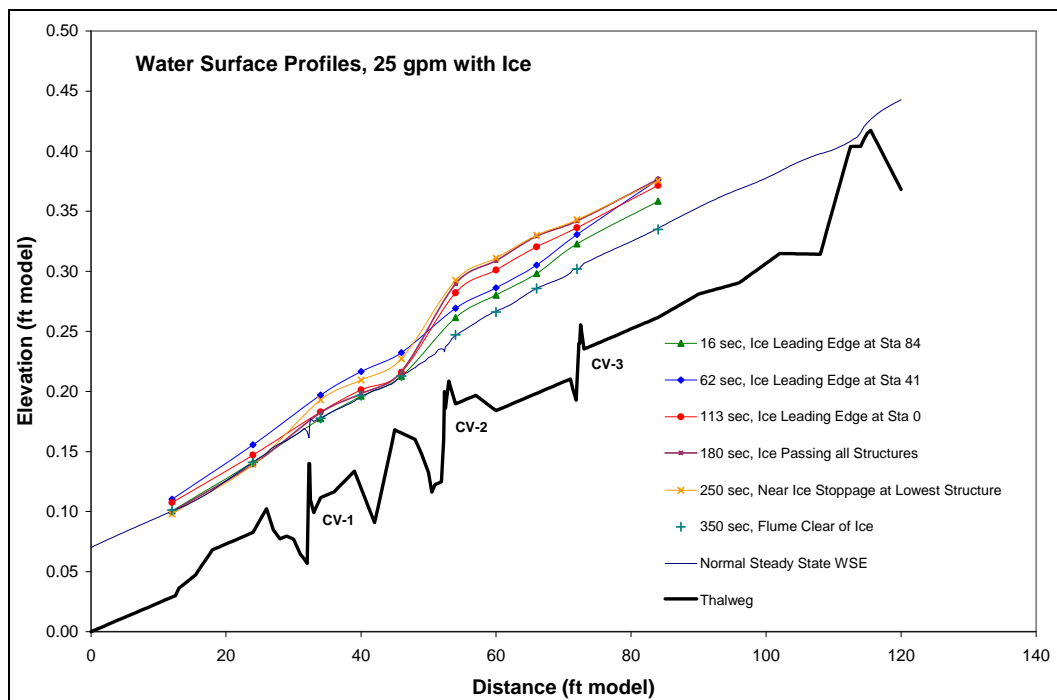


Figure 15. Water surface profiles during 25-gpm ice passage test with structures.
A near ice stoppage occurred at the lowest structure at about 250 sec.

4.1.3. Ice Effects on Structures

During both ice run tests with the structures in place, the ice damaged the center portions of the cross vanes (Fig. 16). The gray structure rocks were displaced downstream of the underlying orange footer rocks, which remained in place. These results, though useful in a qualitative sense, cannot reliably be scaled to prototype. This is because Froude similitude relationships, which are accurate for scaling gravity-dominated open-channel flow parameters such as depth and velocity, apply less well to the complex interaction of ice forces on bed material.



Figure 16. Damage to Cross Vane 2 during ice run.

4.2. Numerical Model Results

As described in Section 2.2, two numerical simulations were done; the first at a prototype flow equivalent to 50-gpm model with a typical ice discharge of $6.9 \text{ m}^3/\text{s}$, and the second with a heavy ice discharge of $13.7 \text{ m}^3/\text{s}$. Unlike the flume experiments where a surge followed the ice release, the ice discharge in the simulations was more or less steady.

For the “typical” ice discharge of $6.9 \text{ m}^3/\text{s}$ carried by a steady water discharge of $55.6 \text{ m}^3/\text{s}$ (50 gpm model), the ice passed through the model

domain without jamming for the entire five-hour duration of the simulation. In the heavy ice discharge simulations ($Q_i = 13.7 \text{ m}^3/\text{s}$), the ice progressively thickened until jamming at the downstream cross vane shortly after Hour 2. Figures 17 and 18 compare ice and water surface profiles for the typical and heavy ice discharge cases, respectively, while Figures 19 and 20 show ice thickness and ice velocity distributions for the two cases.

For the typical ice discharge of $6.9 \text{ m}^3/\text{s}$, conditions were relatively steady state throughout the simulation in that ice parcels traveled through the domain at their initial thickness of 0.3 m, increasing to only about 0.5 m immediately upstream of the cross vanes (Figures 17 and 19). In the heavy ice discharge case of $13.7 \text{ m}^3/\text{s}$, the ice accumulation upstream of the lowest cross vane thickens to about 2.5 m, jamming shortly after the two-hour mark (Figures 18 and 20).

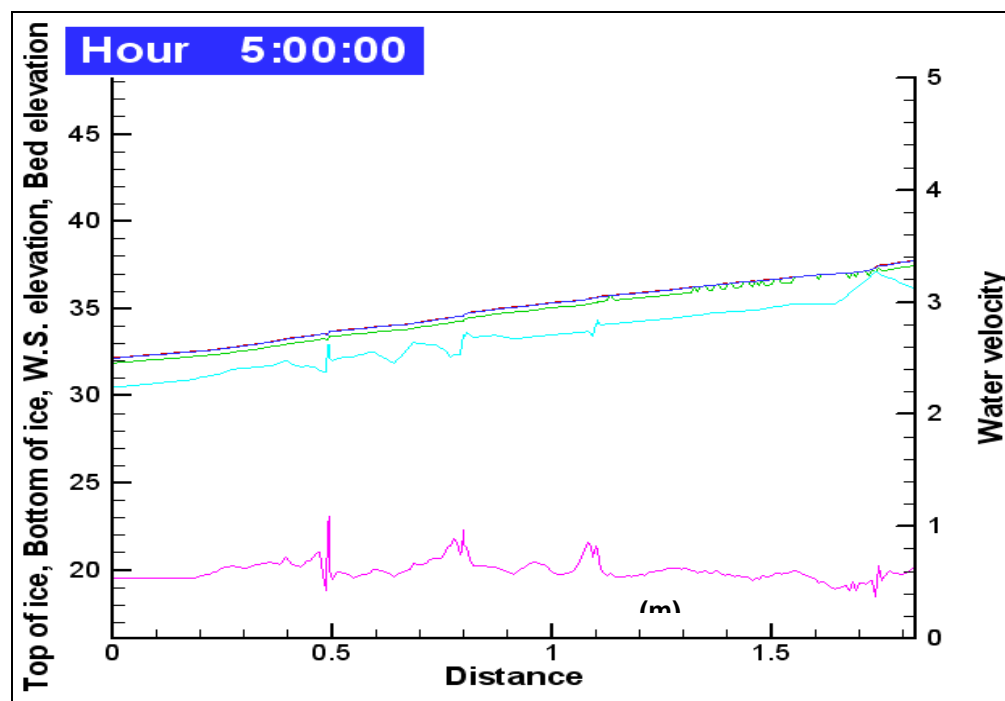


Figure 17. Simulated water, ice, and bed profiles (top) and average water velocity (bottom) for the typical ice case ($Q_i = 6.9 \text{ m}^3/\text{s}$). Relatively steady state conditions.

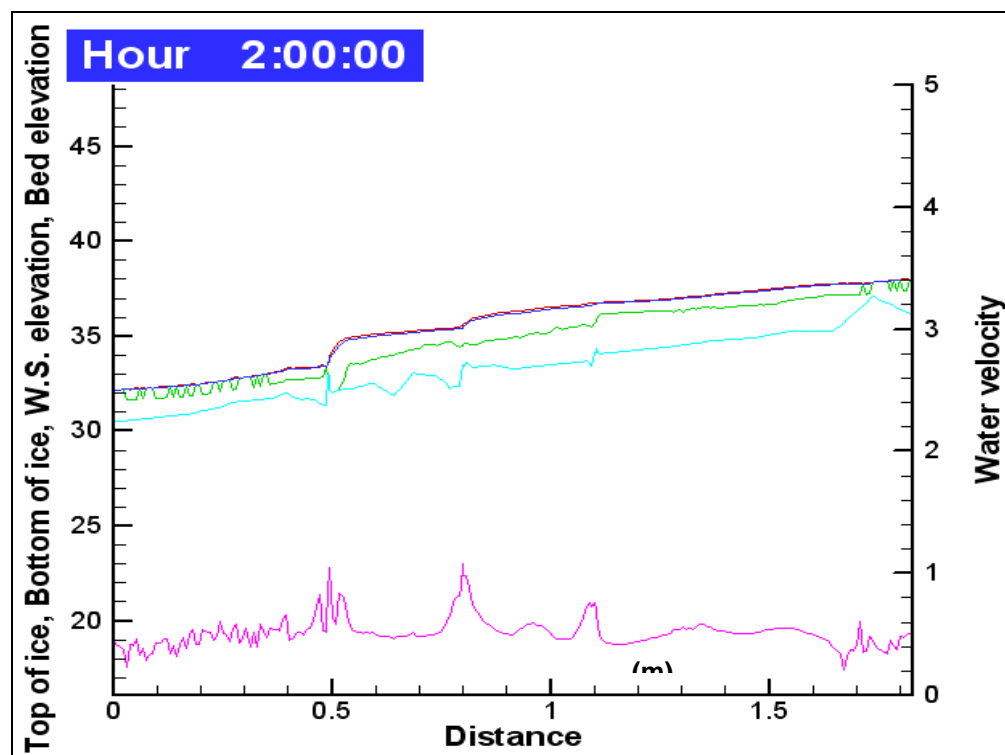


Figure 18. Simulated water, ice, and bed profiles (top) and average water velocity (bottom) for the heavy ice case ($Q_i = 13.7 \text{ m}^3/\text{s}$) just before jamming.

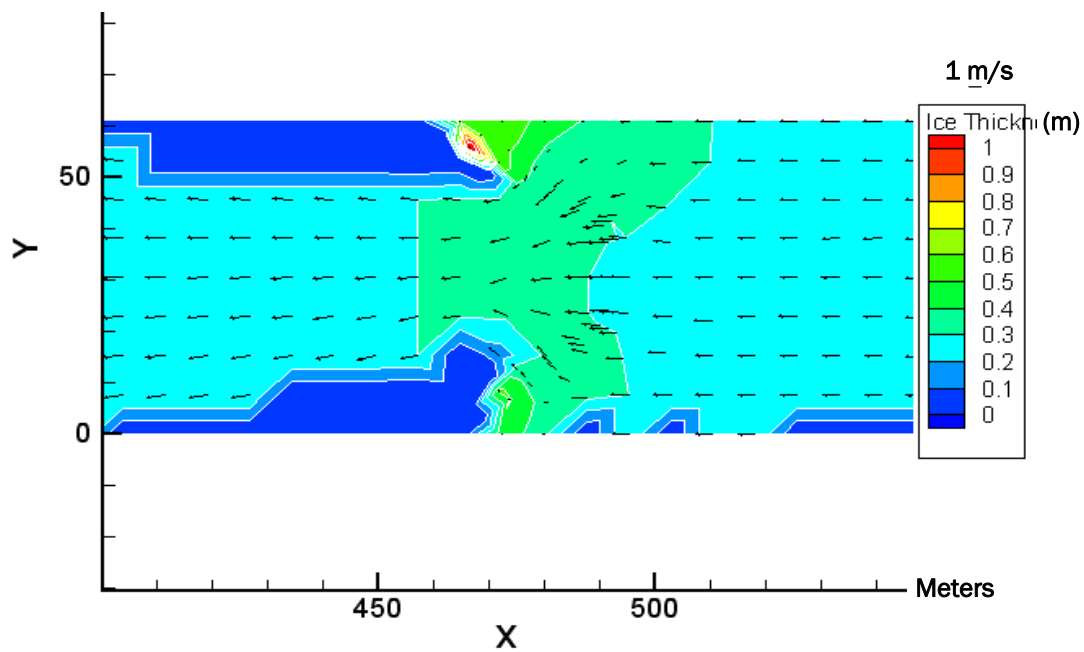


Figure 19. Ice thickness and ice velocity in the vicinity of the downstream cross vane for typical ice case ($Q_i = 6.9 \text{ m}^3/\text{s}$) under relatively steady-state conditions.

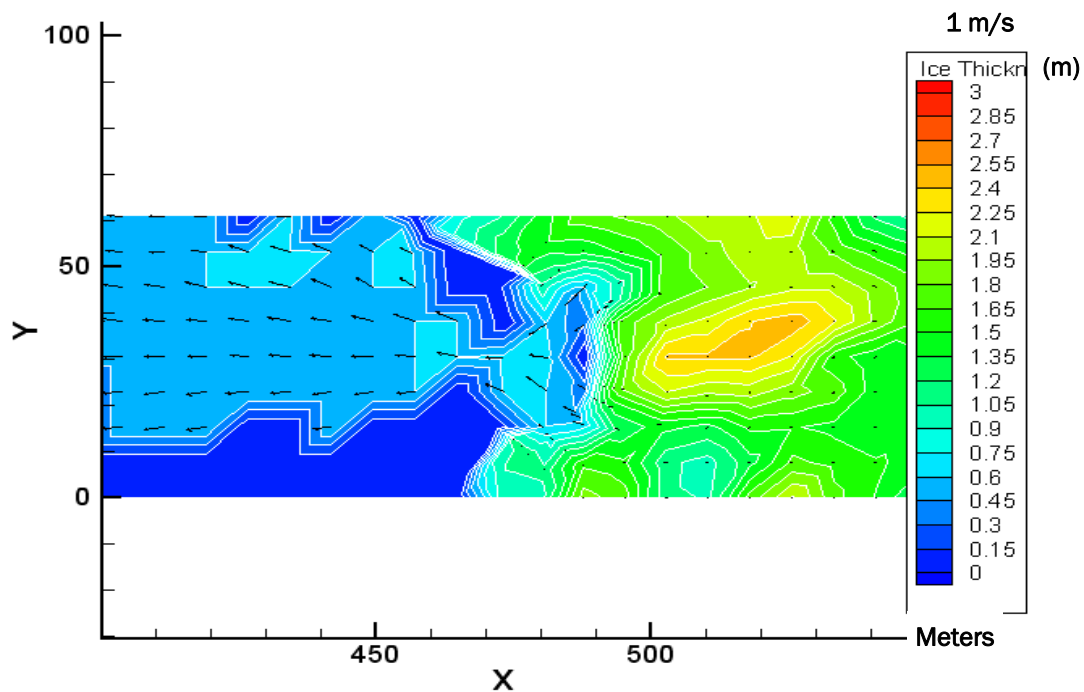


Figure 20. Ice thickness and ice velocity in the vicinity of the downstream cross vane for heavy ice case ($Q_i = 13.7 \text{ m}^3/\text{s}$) just before jamming.

5 Summary and Conclusions

This study used physical and numerical models to examine the effect of cross-vane structures on the ice conveyance during breakup for relatively low water flow and high ice discharge conditions. Three cross-vane structures were built in a straight moveable bed flume assuming a model-to-prototype scale of 1:50. Ice was released at two water flows and two ice discharges to determine whether the structures increased the potential for ice jam formation.

The flume experiments reasonably reproduced the hydraulic, scour, and ice transport processes one would expect on a normal flow, gravel-to-cobble bedded section of river of moderate steepness, with and without the structures in place. By increasing flume bed slope and discharge, scour holes developed downstream of the structures, similar to those observed and measured in the field.

In the flume experiments, the cross-vane structures delayed, but never completely stopped, the ice run, even under conditions of low water flow (50 gpm) and high ice discharge (≥ 0.05 cfs) where one would expect jamming. The moving ice did thicken to the channel bed, displacing some of the structure rocks. A possible reason for non-occurrence of jams with the structures in place is the increased water velocity through the gap, which maintained the ice conveyance capacity even though the effective flow area was reduced. Another reason is that the internal strength of the plastic ice material ϕ may be considerably less than the internal strength of a granular accumulation of natural ice. Finally, the ice in the physical model may have failed to jam as a result of the surge of water that accompanied the ice release, and also the shorter duration of the physical model tests compared to the longer, more steady-state numerical simulations.

In the numerical simulations, the ice run jammed at the full-scale equivalent of 50 gpm under conditions of relatively heavy ice discharge (0.028-cfs model). Under equivalent conditions of water flow and ice discharge, ice passed continuously through the physical model, thickening slightly upstream of the cross vanes. The calibration parameters used in the DynaRICE simulations (Table 2) are based on field observations and

accepted default values, and it is likely that the numerical model results are closer to reality than the 1:50-scale flume results using plastic ice.

In spite of the disagreement between physical and numerical model predictions of ice jam initiation, the two models produced very similar results in terms of hydraulic and ice passage processes. The surface flow patterns and velocity distributions in the vicinity of the vanes were alike, and the ice run thickened and slowed upstream of the vanes similarly, in the flume and computer models.

Though the flume experiments did not demonstrate with certainty that cross-vane structures increase the potential for ice jamming, this should not be taken as a sign that the structures necessarily improve ice conveyance through a reach of river. Recall that, in the heavy ice case of the numerical simulations, the structures did cause jamming.

Study results support existing design guidance for grade-control structures that recommends placing them in free-flowing sections of river rather than pool or backwater reaches, which are naturally more prone to ice jamming. Also, structures should not be placed in reaches with a history of ice jams or ice-related flooding, as these structures may exacerbate the problem, and, even if they do not, the structures may be perceived as the cause of future ice jams.

The flume experiments demonstrated at least qualitatively that, under conditions of heavy ice passage, displacement of structural rocks is possible, particularly in the central section. Damage from moving ice could mean higher maintenance costs when locating these structures on northern rivers; and this has been observed at some field sites in northern Vermont (Tuthill 2008). Lowering the center portion of the structure to the bed elevation may decrease the potential for ice damage at the expense of other design objectives such as flow diversity or grade control. Existing design guidance for riprap in ice-affected streams is quite conservative, recommending a median diameter of structure rocks two to three times the ice thickness to assure a 15 percent or less probability of failure (Sodhi 1999).

Although this study improves our understanding of the interaction of ice hydraulics on in-stream structures and cross vanes in particular, it falls short of its objective of replicating flume results in the DynaRICE simulations. The ability to reproduce field-observed or experimental results with the numerical model will be a very valuable design tool. To this end, further experiments and simulations are proposed.

Since it is doubtful how well the 1:50 plastic ice tests represent ice jamming conditions on a real river, further tests should use real ice at a larger scale, e.g., 1:15. These experiments would be conducted in a fixed-bed model with both a straight and a bend section. Parallel simulations would be conducted using DynaRICE, and every effort would be made to maintain equivalent conditions in the physical and numerical models.

Another important area where design guidance is lacking concerns the effect of in-stream structures on ice processes during the freezeup period. Future research and lab experiments should address this deficiency.

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Appendix A: Summary of Flume Tests

Test #	Date	Condition *	Discharge		Normal Depth		Average Velocity		Slope	Results	Calculated Manning's n	
			(gpm mod)	(cfs prot)	(ft mod)	(ft prot)	(cm/s mod)	(ft/s prot)			Model	Full scale
1	14-Apr	OW-B	157	6184	0.16	8.0	18.2	4.2	0.0024	no sediment movement	0.036	0.069
2	14-Apr	OW-B	200	7878	0.18	9.0	21.0	4.9	0.0024	no sediment movement	0.034	0.065
3	14-Apr	OW-B	300	11817	0.22	11.0	25.0	5.8	0.0024	no sediment movement	0.032	0.062
4	14-Apr	OW-B	400	15755	0.25	12.5	30.0	7.0	0.0024	finer moving	0.029	0.057
5	14-Apr	OW-B	25	985	0.07	3.5	12.5	2.9	0.0024	no sediment movement	0.030	0.058
6	17-Apr	OW-B	50	1969	0.11	5.5	11.7	2.7	0.0024	no sediment movement	0.044	0.084
7	17-Apr	I-B	25	985	0.07	3.5	12.5	2.9	0.0024	All ice passed without jamming	0.030	0.058
8	18-Apr	I-B	50	1969	0.11	5.5	11.7	2.7	0.0024	All ice passed without jamming	0.044	0.084
9	25-Apr	OW-S	360	14180	0.24	12.0	26.2	6.1	0.0035	Some bed movement but no appreciable scour	0.040	0.076
10	25-Apr	OW-S	360	14180	0.20	10.0	30.5	7.1	0.0057	Some bed movement but no appreciable scour	0.038	0.074
11	26-Apr	OW-S	467	18395	0.20	10.0	39.6	9.2	0.0097	Live bed scour, Ran 18 hours	0.039	0.074
12	26-Apr	OW-S	157	6184	0.18	8.8	18.2	4.2	0.0024	Document bed geometry, depths, velocities	0.038	0.074
13	28-Apr	I-S	50	1969	0.11	5.5	12.5	2.9	0.0024	Structures slow ice but all ice passes	0.041	0.078
14	28-Apr	I-S	25	985	0.07	3.5	11.7	2.7	0.0024	Ice nearly jams at structures but eventually passes	0.032	0.062

* OW-B Open water-Baseline conditions
OW-S Open water-Structures
I-B Ice-Baseline conditions
I-S Ice-Structures

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14. ABSTRACT In recent years, channel restoration and streambank stabilization projects have been turning towards "natural" methods, such as cross vanes and rock weirs. Successful applications help control bed and bank erosion, provide flow diversity, re-connect floodplains, and improve habitat for fish and wildlife. Currently little design guidance is available for constructing these structures on ice-affected rivers. This study used physical and numerical models to address the impact of ice runs on in-stream structures. A series of cross vane structures were tested, under conditions of an ice run, in a straight model flume with a moveable bed. Physical model results were then compared to numerical simulations using the state-of-the art DynaRICE ice-hydraulic model. Study results support existing design guidance for grade-control structures that recommends placing them in free-flowing sections of river rather than backwater reaches, which are naturally more prone to ice jamming. The two models produced very similar results in terms of hydraulic and ice passage processes and improved our understanding of the interaction of ice hydraulics on in-stream structures. This study fell short of replicating the physical model results in the numerical model. Further experiments and simulations are proposed to better simulate ice jam conditions in the physical model.					
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